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Comparative analysis of alternative fuels for internal combustion engines: biofuels, synthetic fuels and hydrogen

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Abstract

This research paper presents a comprehensive comparative analysis of alternative fuels for internal combustion engines (ICEs), focusing on biofuels, synthetic fuels, and hydrogen. As the automotive industry faces increasing pressure to reduce greenhouse gas emissions and dependence on fossil fuels, these alternatives have emerged as potential solutions. This study evaluates these fuel options across multiple dimensions, including production methods, energy density, emissions profiles, compatibility with existing infrastructure, economic viability, and life cycle assessment. The findings indicate that each fuel type offers distinct advantages and limitations, suggesting that a diversified approach to alternative fuels may be necessary during the energy transition period. The study concludes with recommendations for policy frameworks and research directions to optimize the implementation of these alternative fuels in transportation sectors.

Keywords: Alternative Fuels; Internal Combustion Engines; Biofuels; Synthetic Fuels; Hydrogen; Sustainability; Emissions Reduction

1. Introduction

The transportation sector accounts for approximately 24% of direct CO_2 emissions from fuel combustion globally, with road vehicles responsible for nearly three-quarters of this contribution (IEA, 2021). As concerns about climate change, air quality, and energy security intensify, there is growing interest in alternative fuels that can reduce the environmental impact of internal combustion engines (ICEs) while maintaining their performance advantages. While electrification represents a significant pathway for decarbonization, ICEs are projected to remain dominant in certain transportation segments for decades to come, particularly in heavy-duty vehicles, marine applications, and regions with limited charging infrastructure (Reitz et al., 2020).

This research examines three primary categories of alternative fuels that can be used in ICEs with varying degrees of modification: biofuels derived from biomass, synthetic fuels produced through chemical processes, and hydrogen as a combustion fuel. Each of these alternatives presents unique characteristics that influence their suitability for different applications and their potential to contribute to decarbonization goals.

The objectives of this study are to

- Evaluate the production pathways, technical characteristics, and performance attributes of biofuels, synthetic fuels, and hydrogen
- Assess the environmental impacts of these fuels across their entire life cycle
- Analyze economic considerations including production costs and infrastructure requirements
- Identify the most promising applications for each fuel type

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- Recommend strategies for optimizing the deployment of these alternatives in the transportation sector

2. Methodology

This research employs a multi-criteria analysis framework to evaluate and compare alternative fuels for ICEs. Data was collected from peer-reviewed literature, industry reports, technical specifications, and government publications from 2015 to 2022. The evaluation criteria include:

- Energy density and specific energy
- Production efficiency and scalability
- Well-to-wheel greenhouse gas emissions
- Air pollutant emissions (NOx, SOx, particulate matter)
- Compatibility with existing engines and infrastructure
- Production costs and economic viability
- Technology readiness level
- Life cycle sustainability impacts

The analysis incorporates both quantitative metrics and qualitative assessments to provide a holistic comparison of these alternative fuel options across diverse operating conditions and applications [1].

3. Biofuels

3.1. Classification and Production Pathways

Biofuels are derived from biomass through various conversion processes. They are typically categorized as:

- First-generation biofuels: Produced from food crops (corn, sugarcane, vegetable oils)
- Second-generation biofuels: Derived from non-food crops, agricultural residues, and waste materials
- Third-generation biofuels: Produced from algae and microorganisms
- Fourth-generation biofuels: Using genetically modified organisms designed specifically for fuel production

The primary biofuels currently used in ICEs include

- Bioethanol: Produced through the fermentation of sugars from starch or cellulosic feedstocks
- Biodiesel: Manufactured through transesterification of vegetable oils or animal fats
- Hydrotreated Vegetable Oil (HVO): Created by hydroprocessing of vegetable oils or waste fats
- Biogas/Biomethane: Generated through anaerobic digestion of organic materials

Table 1 summarizes the production pathways and feedstocks for major biofuel categories.

3.2. Technical Properties and Engine Performance

Biofuels exhibit varying physical and chemical properties that influence their compatibility with conventional engines and their performance characteristics. Figure 1 illustrates the energy density comparison between conventional fuels and various biofuels.

Bioethanol has a lower energy density than gasoline (approximately 33% less), resulting in increased fuel consumption. However, its higher-octane rating allows for increased compression ratios, potentially improving engine efficiency. Biodiesel offers energy density similar to conventional diesel (approximately 8-10% lower) and provides enhanced lubricity that can extend engine life (Knothe & Razon, 2017).

Table 1 Production Pathways and Feedstocks for Major Biofuel Categories

Biofuel Type	Primary Feedstocks	Production Process	Yield Range (L/ha/year)	Current Market Share (%)
Bioethanol	Corn, sugarcane, wheat, lignocellulosic biomass	Fermentation, distillation	1,400-8,000	65% of global biofuel production

Biodiesel	Rapeseed, soybean, palm oil, used cooking oil	Transesterification	500-6,000	30% of global biofuel production
HVO/Renewable diesel	Vegetable oils, waste animal fats	Hydrotreatment	600-5,500	3% of global biofuel production
Biogas/Biomethane	Organic waste, manure, sewage sludge	Anaerobic digestion	N/A (depends on waste input)	2% of global biofuel production

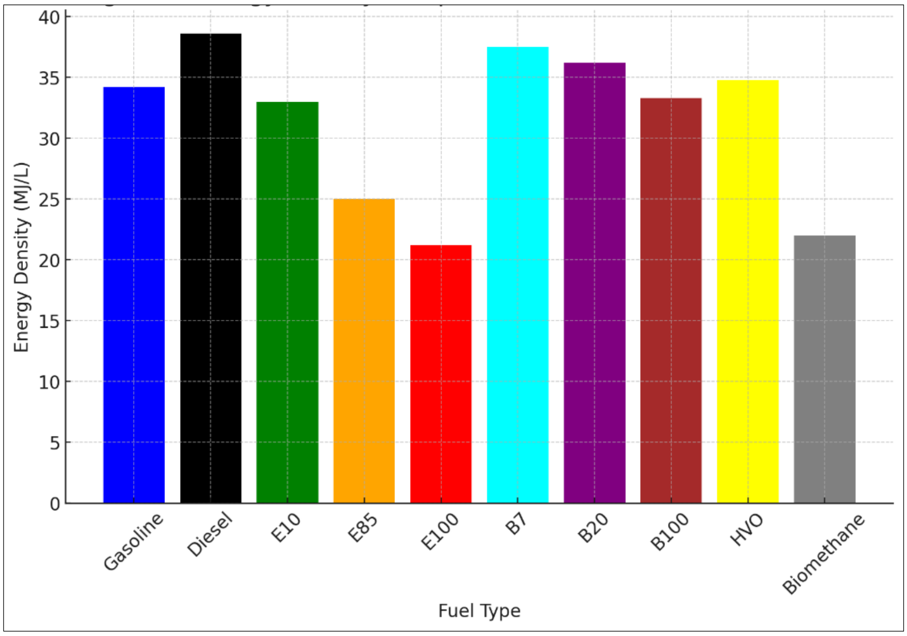

Figure 1 Energy Density Comparison of Conventional and Biofuels

HVO closely resembles conventional diesel in its chemical properties, allowing for "drop-in" compatibility without engine modifications. Biomethane requires specialized storage systems but can be used effectively in natural gas engines.

Engine performance tests have shown that:

- E10 (10% ethanol blend) can be used in most gasoline engines without modifications
- Higher ethanol blends (E85, E100) require flex-fuel vehicle technology
- B7 and B20 (7% and 20% biodiesel blends) are compatible with most diesel engines
- B100 (pure biodiesel) may require fuel system modifications in older engines
- HVO can be used in any proportion with conventional diesel without modifications
- Biomethane requires dedicated natural gas engines or conversion kits

3.3. Environmental Impacts and Sustainability Considerations

The environmental profile of biofuels varies significantly depending on feedstock, production methods, and end-use applications. Figure 2 presents the well-to-wheel greenhouse gas (GHG) emissions of various biofuels compared to their fossil counterparts.

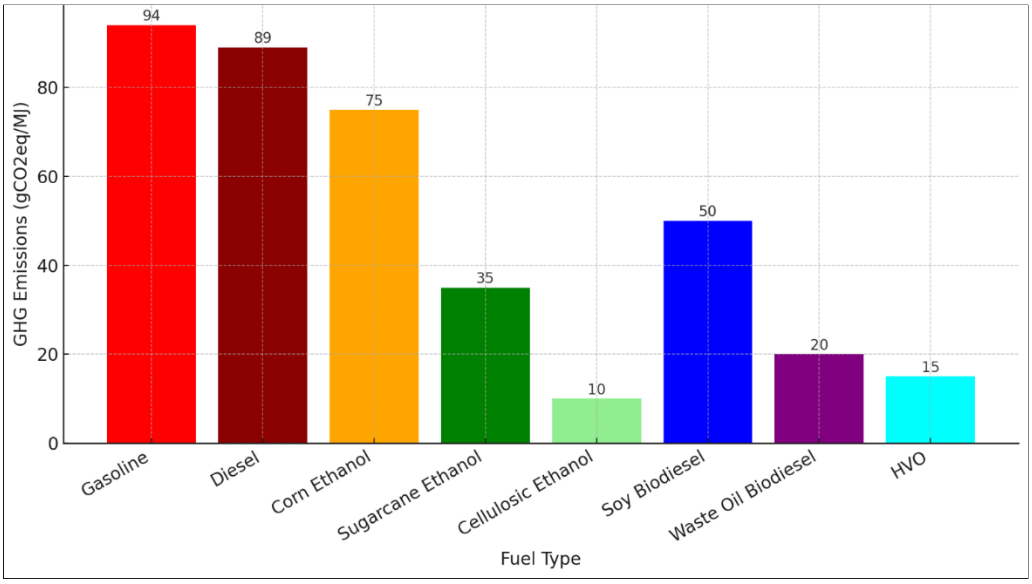

Figure 2 Well-to-Wheel GHG Emissions Comparison

While biofuels generally offer GHG reductions compared to fossil fuels, the magnitude of these benefits depends largely on:

- Feedstock cultivation practices: Land use change can significantly impact carbon balance
- Processing efficiency: Energy-intensive production can offset emissions benefits
- Transportation logistics: Distance between production and consumption points
- End-use efficiency: Engine optimization for specific biofuels

Sustainability concerns for biofuels include:

- Food vs. fuel competition: Particularly relevant for first-generation biofuels
- Land use change: Direct and indirect effects on carbon stocks and biodiversity
- Water usage: Some feedstocks require significant irrigation
- Agrochemical inputs: Fertilizers and pesticides impact environmental footprint
- Biodiversity impacts: Monoculture production systems can reduce habitat diversity

Second and third-generation biofuels address many of these concerns but face technical and economic challenges to widespread deployment.

4. Synthetic fuels

4.1. Definition and Production Pathways

Synthetic fuels (synfuels) are liquid or gaseous fuels produced through chemical processes from various carbon sources. Unlike biofuels, which derive carbon from contemporary biomass, synthetic fuels can utilize fossil carbon (coal, natural gas) or captured carbon dioxide. The primary categories of synthetic fuels include:

- Fischer-Tropsch (FT) fuels: Produced by converting synthesis gas (syngas) into liquid hydrocarbons
- Methanol-to-gasoline (MTG): Converting methanol to gasoline-range hydrocarbons
- Power-to-liquid (PtL) fuels: Using renewable electricity to produce hydrogen, which is combined with captured CO2 to create liquid fuels
- Power-to-gas (PtG): Using renewable electricity to produce synthetic methane or other gaseous fuels

The production pathways for these synthetic fuels vary in their technological maturity, energy efficiency, and environmental impact, as summarized in Table 2.

Table 2 Production Pathways and Characteristics of Major Synthetic Fuel Categories

Synthetic Fuel Type	Carbon Source	Energy Source	Production Steps	Technology Readiness Level	Energy Efficiency (%)
Coal-to-liquid (CTL)	Coal	Fossil	Coal gasification → Syngas production → Fischer-Tropsch synthesis	Commercial (TRL 9)	40-50%
Gas-to-liquid (GTL)	Natural gas	Fossil	Steam reforming → Syngas production → Fischer-Tropsch synthesis	Commercial (TRL 9)	60-65%
Power-to-liquid (PtL)	Captured CO2	Renewable electricity	Electrolysis → H2 production → CO2 hydrogenation → Fischer-Tropsch synthesis	Demonstration (TRL 6-7)	40-50%
Power-to-methane	Captured CO2	Renewable electricity	Electrolysis → H2 production → Methanation	Demonstration (TRL 7-8)	50-65%

4.2. Technical Properties and Performance Characteristics

Synthetic fuels can be designed to have specific properties that optimize engine performance and emissions profiles. This "designer fuel" capability represents a significant advantage over conventional fossil fuels and some biofuels. Table 3 compares key fuel properties of synthetic fuels with conventional fuels [2].

Table 3 Comparison of Key Fuel Properties

Fuel Type	Cetane Number (Diesel) / Octane Number (Gasoline)	Energy Density (MJ/kg)	Cold Flow Properties (°C)	Aromatic Content (%)	Sulfur Content (ppm)
Diesel	40–55	42–45	-10 to -20	20–30	<10–500
Gasoline	87–98	42–44	-60 to -40	20–50	<10–100
FT Diesel	70–80	44–45	-40 to -60	<1	<10
PtL Gasoline	95–100	42–44	-60 to -40	<1	<10
Biodiesel	47–65	37–40	0 to -10	0	<10
HVO	75–90	44–46	-40 to -20	0	<10

Notable performance characteristics of synthetic fuels include

- High purity: Lower contaminant levels (sulfur, metals) than conventional fuels
- Tunable properties: Cetane/octane numbers can be optimized for specific engines
- Excellent combustion characteristics: Reduced particulate matter and NOx emissions
- Drop-in capability: Most synthetic fuels can be used in existing engines without modification
- Stability: Longer shelf life than many biofuels

Engine tests with Fischer-Tropsch diesel have demonstrated 5-40% reductions in particulate matter emissions and up to 20% reduction in NOx emissions compared to conventional diesel (de Klerk, 2020). The absence of aromatic compounds and the highly paraffinic nature of many synthetic fuels contribute to cleaner combustion.

4.3. Environmental and Economic Considerations

The environmental impact of synthetic fuels varies dramatically depending on the carbon source and energy input for production. Figure 4 illustrates the well-to-wheel carbon intensity of various synthetic fuel pathways.

Table 4 Well-to-Wheel Carbon Intensity of Synthetic Fuel Pathways

Fuel Type	**Well-to-Wheel GHG Emissions (gCO_2eq/MJ)**
Conventional Diesel/Gasoline	90 - 100
Coal-to-Liquid (CTL)	200 - 250
Gas-to-Liquid (GTL)	90 - 110
Power-to-Liquid (PtL) - Grid Electricity	50 - 80
Power-to-Liquid (PtL) - Renewable Electricity	0 - 20

Key environmental considerations include

- CTL and GTL pathways: Generally, result in higher life cycle emissions than conventional petroleum fuels
- PtL with renewable electricity: Can achieve 70-90% reduction in GHG emissions compared to fossil fuels
- Carbon circularity: PtL fuels using atmospheric CO2 capture can approach carbon neutrality
- Land use efficiency: Synthetic fuel production requires significantly less land area than biofuels

Economic challenges remain substantial for many synthetic fuel pathways:

- Production costs range from 2-5 times higher than conventional fossil fuels
- Capital-intensive facilities require large-scale production to achieve economies of scale
- Process efficiency improvements and carbon pricing mechanisms may improve economic viability
- Integration with renewable power generation could provide valuable energy storage functionality

5. Hydrogen

5.1. Production Methods and Classification

Hydrogen as a fuel for ICEs is typically classified according to its production method, which significantly impacts its carbon footprint:

- Grey hydrogen: Produced from natural gas through steam methane reforming without carbon capture
- Blue hydrogen: Produced from fossil fuels with carbon capture and storage (CCS)
- Green hydrogen: Produced through electrolysis of water using renewable electricity
- Turquoise hydrogen: Produced through methane pyrolysis, generating solid carbon instead of CO2

Table 5 summarizes the key characteristics of these hydrogen production pathways.

Table 5 Comparison of Hydrogen Production Pathways

Production Pathway	**Primary Energy Source**	**Process Technology**	**Carbon Intensity (kgCO2e/kgH2)**	**Production Cost Range ($/kg)**	**Energy Efficiency (%)**
Steam methane reforming (Grey H2)	Natural gas	Catalytic conversion	9-12	1.0-2.0	65-75%
SMR with CCS (Blue H2)	Natural gas	Catalytic conversion with carbon capture	1-4	1.5-3.0	55-65%
Electrolysis (Green H2)	Renewable electricity	PEM/Alkaline/Solid oxide electrolysis	0-2	3.0-6.0	60-80%
Methane pyrolysis (Turquoise H2)	Natural gas	Thermal decomposition	1-3	1.5-3.5	40-60%

5.2. Hydrogen ICE Technology and Performance

Hydrogen-fueled internal combustion engines (H2ICEs) represent an alternative to fuel cells for utilizing hydrogen in transportation. These engines can be purpose-built for hydrogen or converted from conventional engines. Figure 5 illustrates the key differences between hydrogen and conventional fuel combustion in ICEs [3]. Key technical aspects of H2ICEs include

- High flame speed: Hydrogen combusts approximately 7 times faster than gasoline
- Wide flammability range: 4-75% hydrogen in air (compared to 1.4-7.6% for gasoline)
- Low ignition energy: Approximately one-tenth the ignition energy of gasoline
- High auto-ignition temperature: 585°C (compared to 230-480°C for gasoline)
- Zero carbon emissions: Water vapor is the primary combustion product
- Potential for NOx formation: Due to high combustion temperatures

H2ICEs achieve thermal efficiencies of 35-45%, comparable to advanced diesel engines and higher than typical gasoline engines (Verhelst et al., 2019). However, volumetric energy density challenges necessitate specialized fuel storage systems, typically as compressed gas (350-700 bar) or cryogenic liquid (-253°C).

Engine modifications for hydrogen operation include

- Direct injection systems to prevent pre-ignition and backfiring
- Modified ignition systems and timing
- Reinforced components to handle higher combustion pressures
- Specialized lubricants to handle water formation
- Advanced thermal management systems

5.2.1. 5.3 Infrastructure, Safety, and Economic Considerations

Hydrogen infrastructure for transportation faces significant challenges

- Production scaling: Current global hydrogen production is primarily for industrial uses
- Distribution networks: Limited hydrogen pipeline infrastructure exists
- Refueling stations: High capital costs ($1-2 million per station)
- Storage requirements: Specialized high-pressure or cryogenic systems

Safety considerations for hydrogen include

- Leak detection: Hydrogen is colorless and odorless
- Wide flammability range: Ignites easily in a broad concentration range
- Invisible flame: Hydrogen flames are nearly invisible in daylight
- Embrittlement: Hydrogen can weaken certain metals over time

Economic analysis indicates hydrogen ICEs may offer advantages over hydrogen fuel cells in certain applications:

- Lower system costs (approximately 30-50% of equivalent fuel cell powertrains)
- Leveraging existing engine manufacturing capabilities
- Dual-fuel capability (hydrogen/gasoline) possible in some designs
- Lower sensitivity to hydrogen purity requirements

6. Comparative analysis

6.1. Technical Performance Comparison

Table 6 provides a comprehensive comparison of key technical parameters across the alternative fuel categories discussed.

Table 6 Technical Performance Comparison of Alternative Fuels

Parameter	Energy density (MJ/L)	Specific energy (MJ/kg)	Octane/Cetane number	Cold weather performance	Storage stability	Water tolerance	Materials compatibility
Gasoline	32-35	42-44	87-98 (RON)	Excellent	Excellent	Poor	Standard
Diesel	35-38	42-45	40-55 (CN)	Good	Good	Poor	Standard
Bioethanol	21-24	26-29	102-115 (RON)	Moderate	Poor-Moderate	Excellent	Limited
Biodiesel	33-35	37-40	45-65 (CN)	Poor-Moderate	Moderate	Moderate	Limited
HVO	34-36	43-44	70-90 (CN)	Excellent	Good	Good	Standard
Synthetic Diesel	33-36	43-45	70-90 (CN)	Excellent	Excellent	Excellent	Standard
Synthetic Gasoline	31-34	42-44	95-100 (RON)	Excellent	Excellent	Good	Standard
Hydrogen	8-10 (liquid)	120-142	130+ (RON equivalent)	Moderate	Challenging	N/A	Specialized

6.2. Environmental Impact Assessment

Beyond GHG emissions, Table 7 provides a qualitative assessment of additional environmental impacts.

6.3. Economic Viability and Market Readiness

The economic competitiveness of alternative fuels is a critical factor for market adoption. Figure 7 illustrates the current production cost ranges for various fuel options [4].Table 8 evaluates the market readiness of alternative fuel options.

Table 7 Environmental Impact Assessment of Alternative Fuels

Environmental Factor	Biofuels	Synthetic Fuels	Hydrogen
Land use requirements	High (first-gen) to Moderate (advanced)	Low	Very low
Water consumption	High (crop-based) to Moderate (waste-based)	Moderate to Low	Moderate (electrolysis)
Air quality impact (NOx, PM)	Moderate improvement	Significant improvement	Excellent (minimal NOx)
Biodiversity impact	Moderate to High (feedstock dependent)	Low	Very low
Resource depletion	Low (renewable)	Low to High (depends on pathway)	Low (green H2) to Moderate (blue H2)
Waste generation	Low to Moderate	Low	Very low

Table 8 Market Readiness Assessment

Fuel Type	Technology Readiness Level	Supply Chain Maturity	Scale-up Potential	Policy Support Level	Near-term Outlook
Conventional ethanol	Commercial (TRL 9)	High	Moderate	High	Stable growth
Advanced biofuels	Demonstration to Early Commercial (TRL 6-8)	Low to Moderate	Moderate	High	Gradual expansion
CTL/GTL synthetic fuels	Commercial (TRL 9)	Moderate	High	Low	Limited growth
PtL (e-fuels)	Demonstration (TRL 6-7)	Low	High	Moderate	Significant growth potential
Grey hydrogen	Commercial (TRL 9)	High	High	Low	Limited adoption in ICEs
Green hydrogen	Early Commercial (TRL 7-8)	Low	Very high	High	Growing demonstration projects

7. Application-specific suitability

Different alternative fuels show varying degrees of suitability across transportation segments. Figure 8 presents a heatmap of fuel suitability across vehicle types [5].

Key findings include

- Passenger vehicles: Bioethanol, synthetic gasoline, and hydrogen all viable with appropriate modifications
- Heavy-duty transport: HVO, synthetic diesel, and hydrogen show strongest potential
- Marine applications: Biodiesel, synthetic fuels, and potentially hydrogen for shorter routes
- Aviation: Synthetic jet fuels offer the most promising alternative to conventional jet fuel
- Off-road equipment: Biodiesel and HVO offer near-term solutions

Figure 9 Alternative Fuel Suitability by Application

Alternative Fuel	Passenger Vehicles	Light Commercial Vehicles	Heavy-Duty Trucks	Marine Vessels	Aviation
Bioethanol	High	Medium	Low	Low	Low
Biodiesel	Medium	High	High	Medium	Low
HVO (Hydrotreated Vegetable Oil)	High	High	High	High	Medium
Synthetic Diesel (GTL, PtL)	High	High	High	High	High
Hydrogen (Fuel Cell)	Medium	Medium	High	Low	Low
Hydrogen (Combustion)	Low	Medium	High	Medium	Medium
Ammonia	Low	Low	Medium	High	High
Methanol	Medium	Medium	Medium	High	High
LNG (Liquefied Natural Gas)	Low	Medium	High	High	Low

8. Policy Implications and Recommendations

8.1. Policy Frameworks for Alternative Fuel Adoption

Effective policy mechanisms to accelerate alternative fuel adoption include:

- Carbon pricing: Internalizing external costs of fossil fuels
- Blending mandates: Requiring minimum alternative fuel content
- Tax incentives: Reducing costs for producers and consumers
- Investment support: Financing production facilities and infrastructure
- Research and development funding: Advancing technology readiness
- Regulatory standards: Emissions and sustainability criteria

Table 10 evaluates the effectiveness of these mechanisms for each alternative fuel category.

Table 10 Policy Mechanism Effectiveness by Fuel Type

Policy Mechanism	Biofuels	Synthetic Fuels	Hydrogen
Carbon pricing	Moderate	High	High
Blending mandates	High	Moderate	Low
Tax incentives	High	High	High
Investment support	Moderate	High	Very high
R&D funding	Moderate	High	High
Regulatory standards	High	Moderate	Moderate

8.2. Strategic Recommendations

Based on the comparative analysis conducted in this study, the following recommendations are proposed:

- Adopt a diversified approach: No single alternative fuel solution meets all requirements across transportation sectors. A portfolio approach accounts for regional differences in resource availability and infrastructure.
- Prioritize sustainability certification: Implement robust life cycle assessment and sustainability criteria for all alternative fuels to ensure environmental benefits.
- Establish technology-neutral incentives: Focus policies on carbon intensity reduction rather than specific technologies to encourage innovation.
- Invest in infrastructure development: Address the chicken-and-egg problem by supporting refueling/charging infrastructure development.
- Support transitional solutions: Recognize that drop-in fuels (HVO, synthetic fuels) may offer faster decarbonization in existing vehicle fleets.
- Coordinate standards internationally: Harmonize fuel specifications and sustainability criteria to facilitate global markets.
- Integrate with broader energy systems: Consider the role of alternative fuels in energy storage and sector coupling.

9. Conclusion and Future Outlook

This comparative analysis of biofuels, synthetic fuels, and hydrogen for internal combustion engines reveals that each alternative fuel category offers distinct advantages and faces specific challenges. Biofuels provide a mature technology pathway with established production capacity but face feedstock limitations and sustainability concerns. Synthetic fuels offer exceptional compatibility with existing infrastructure and can achieve high environmental performance when produced with renewable energy, though economic viability remains a barrier. Hydrogen presents the highest specific energy and zero carbon emissions at the point of use but requires significant infrastructure development and vehicle modifications.

The future landscape of alternative fuels will likely be characterized by

- Regional specialization based on local resource availability
- Progressive blending and hybridization of fuel types
- Parallel development of electric mobility and alternative fuels
- Sector-specific solutions rather than universal approaches
- Integrated energy system perspectives

In the medium term (2025-2035), drop-in alternatives such as HVO and synthetic fuels may play a crucial transitional role in decarbonizing existing fleets. Longer-term (beyond 2035), more disruptive solutions including advanced biofuels, e-fuels from direct air capture, and green hydrogen could achieve deeper decarbonization as technology costs decrease and infrastructure develops.

Further research is needed to

- Optimize engine designs specifically for alternative fuels
- Develop more efficient production pathways with lower energy requirements
- Refine life cycle assessment methodologies for complex fuel systems
- Evaluate the system-level interactions between alternative fuels and electrification
- Assess the full economic costs and benefits including externalities

As the transportation sector navigates the transition toward carbon neutrality, alternative fuels for internal combustion engines will play a vital role in reducing emissions while leveraging existing assets and infrastructure. Their successful implementation will require coordinated efforts across industry, government, and research institutions to overcome technical, economic, and regulatory barriers.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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